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NASA Technical Memorandum 83115

NASA-TM-83115 19810016677

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FLOW PROPERTIES OF A SERIES OF EXPERIMENTAL THERMOPLASTIC POLYIMIDES

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April 1981

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NF00379

INTRODUCTION

Carbon fiber reinforced composite materials with thermosetting polyimide matrices are attractive for a variety of elevated temperature mechanical and structural applications (refs. 1, 2). These lightweight composites are strong and stiff and typically have more thermal stability than do similar composites with epoxy resin matrices. Such composites, however, tend to be flaw sensitive and have low impact resistance, characteristics which are thought to result from the use of a brittle matrix. One possible method of overcoming these characteristics is to use a thermoplastic matrix. A thermoplastic polyimide, then, might provide thermally stable composites with flaw tolerance and high impact resistance (ref. 3).

The use of a thermoplastic matrix in a continuous fiber composite, however, presents two problems. One problem arises in impregnating the collimated fibers with the polymer to obtain a prepreg tape. As solvent resistance would be needed in many applications, the use of a solvent to dissolve the polymer and facilitate prepregging would be difficult. Moreover, the solvent would have to be removed before or during the molding of the prepreg into a laminate. A hot-melt prepregging system would be more desirable, in which case the melt flow properties of the polymer would be very important. The second problem in thermoplastic matrix composite fabrication arises when the prepreg tape is stacked and molded together under heat and pressure. Again, the polymer must flow. But, since a high glass transition temperature (T_g) is of value in composite applications, and since molding is performed above T_g , the required molding temperatures can become very high. These molding temperatures can be lowered somewhat by using high pressures to obtain sufficient flow. The high pressure approach is of limited value, however, because excessive pressures may lead to fiber breakage and/or misalignment, and will require extremely large forces to mold large composite parts.

Both of these problems, one associated with prepregging, the other associated with molding, concern the flow of the thermoplastic. Therefore, measurements have been made of three experimental thermoplastic polyimides (taken as model polymers without regard to thermal stability) with the objective of relating these properties to required composite processing parameters. The flow properties were measured with a capillary rheometer. Two of the polymers were fabricated with carbon fibers into unidirectional laminates for short beam shear tests.

CHARACTERISTIC TEMPERATURES, K, OF THERMOPLASTIC POLYIMIDES

The three experimental thermoplastic polyimides were supplied in pellet form by the Rohm and Haas Company.* These amorphous polyaliphatic imides (which are not as thermally stable as aromatic polyimides) were intended for use in injection molded parts, not as the matrix for continuous fiber composites. The polymers were designated, for the purpose of this investigation, according to their Vicat softening temperature (ref. 4) as reported by the supplier.

In order to estimate a temperature range for testing and processing, the glass transition temperature (T_g) of each polymer was measured with a torsional braid analyzer (TBA, ref. 5). The braids were dried at 425 K in a nitrogen atmosphere for 1 hour before testing at a rise rate of 3 K/min beginning at 300 K. Initial TBA tests with a given braid showed a slightly lower (3-10 K) T_g than did subsequent tests, suggesting that the as-received polymers contained some residual solvent. Thermogravimetric analyses (TGA, ref. 6) of the polymers were made in a static air atmosphere at a temperature rise rate of 5 K/min beginning at 300 K. The weight-temperature curves and the temperature for 10 percent weight loss were similar for all three polymers, suggesting that they had similar degradation mechanisms. With the TBA results providing a lower range (440-500 K) and the TGA results providing an upper bound (650 K), a test and processing range of 500-600 K was selected for the polymers.

*Use of commercial products or names of manufacturers in this report does not constitute official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

**CHARACTERISTIC TEMPERATURES, K,
OF THERMOPLASTIC POLYIMIDES***

POLYMER	VICAT SOFTENING	GLASS TRANSITION	10% WT LOSS
V-167	440	442	651
V-200	473	477	655
V-230	503	504	653

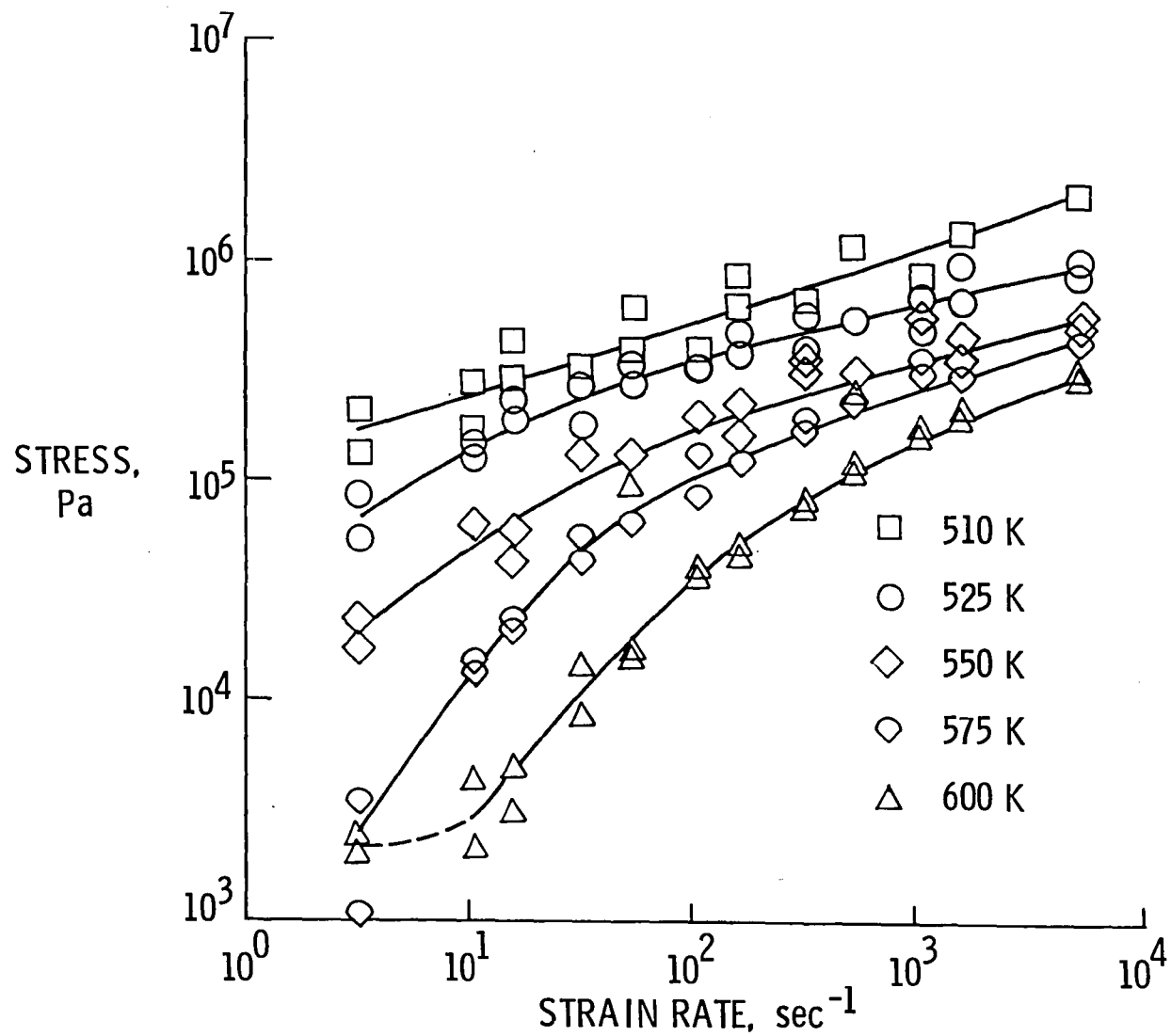
*AMORPHOUS POLYALIPHATIC IMIDE SUPPLIED BY ROHM AND HAAS

FLOW CURVES OF POLYIMIDE V-167

The flow properties of all three polymers were measured with a capillary rheometer (ref. 7). As capillaries with length-to-diameter ratios of 33 or 66 were used, no end correction in the data was required. For the V-167 polymer, a 90 K range of test temperature was investigated, the lowest temperature (510 K) being that for which flow measurements could be made on the rheometer. Below 510 K, the plunger pressure necessary to push the polymer through the capillary exceeded the rheometer load range. At 600 K, for the lowest strain rates ($<10 \text{ sec}^{-1}$), the compressibility of the polymer was such that the slow motion of the plunger was accommodated without polymer flow through the capillary.

Molding pressures associated with typical commercial autoclaves ($\sim 1.4 \text{ MPa}$) would, with the capillaries employed in this study, correlate with stresses in the 10^3 - 10^4 Pa range. Commercial molding presses would correlate with higher stresses, say in the 10^4 - 10^5 Pa range. Most of the measured stresses for the V-167 were within or exceeded these stresses. Hence, processing in conventional facilities would require high temperatures and low strain rates (i.e., long times).

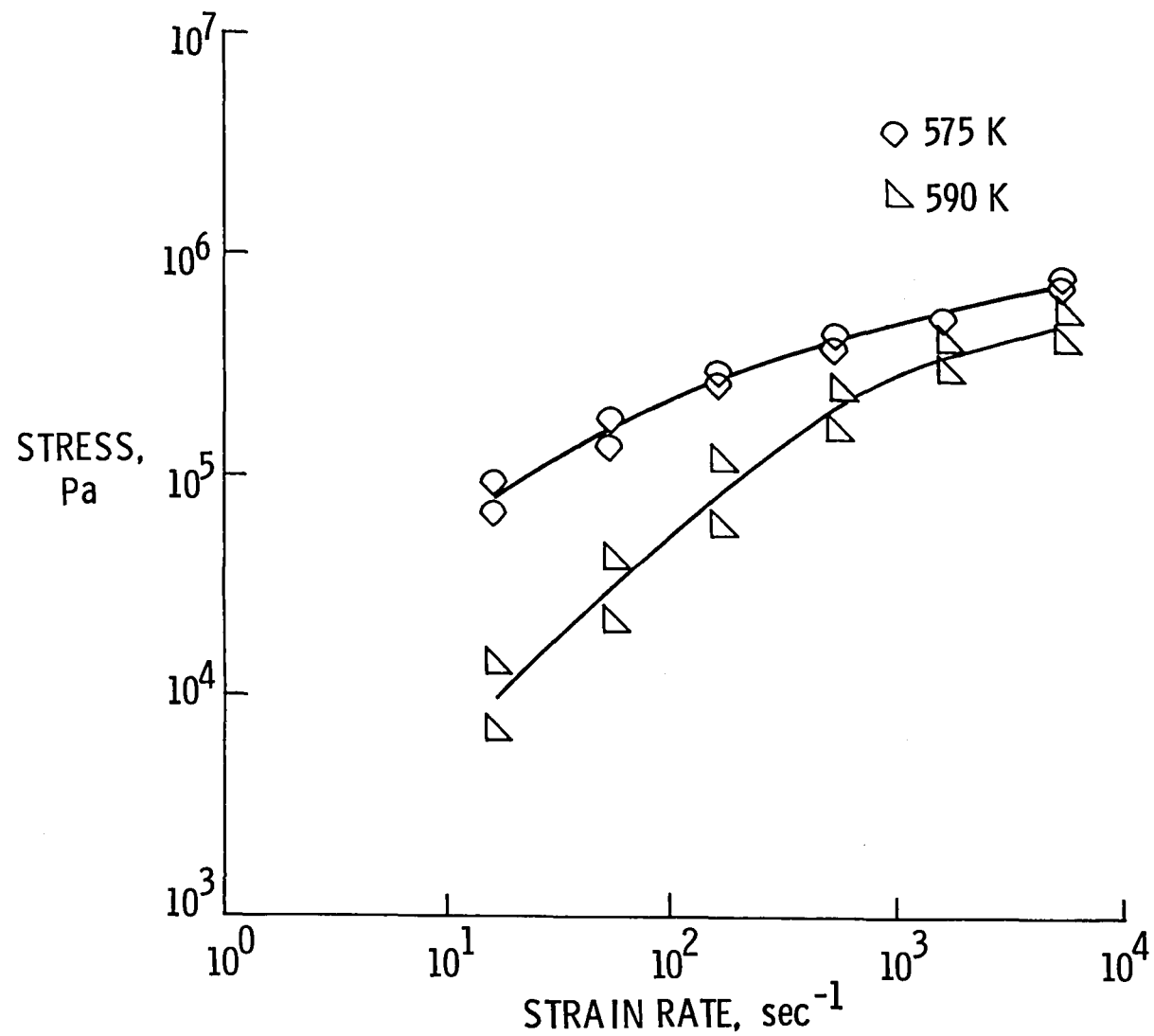
FLOW CURVES OF POLYIMIDE V-167



FLOW CURVES OF POLYIMIDE V-200

Fewer measurements were made on the V-200 compared to the V-167. The lower test temperature (575 K) was chosen so that the pressures required for flow were within the rheometer load range. The upper test temperature (590 K) was used because at 600 K, the polymer crackled and sputtered and released fumes which were assumed to be residual solvent. However, for these two temperatures and a given strain rate, the flow stress for the V-200 was higher than that of the V-167. Such higher stresses are consistent with the higher T_g of the V-200 relative to the V-167.

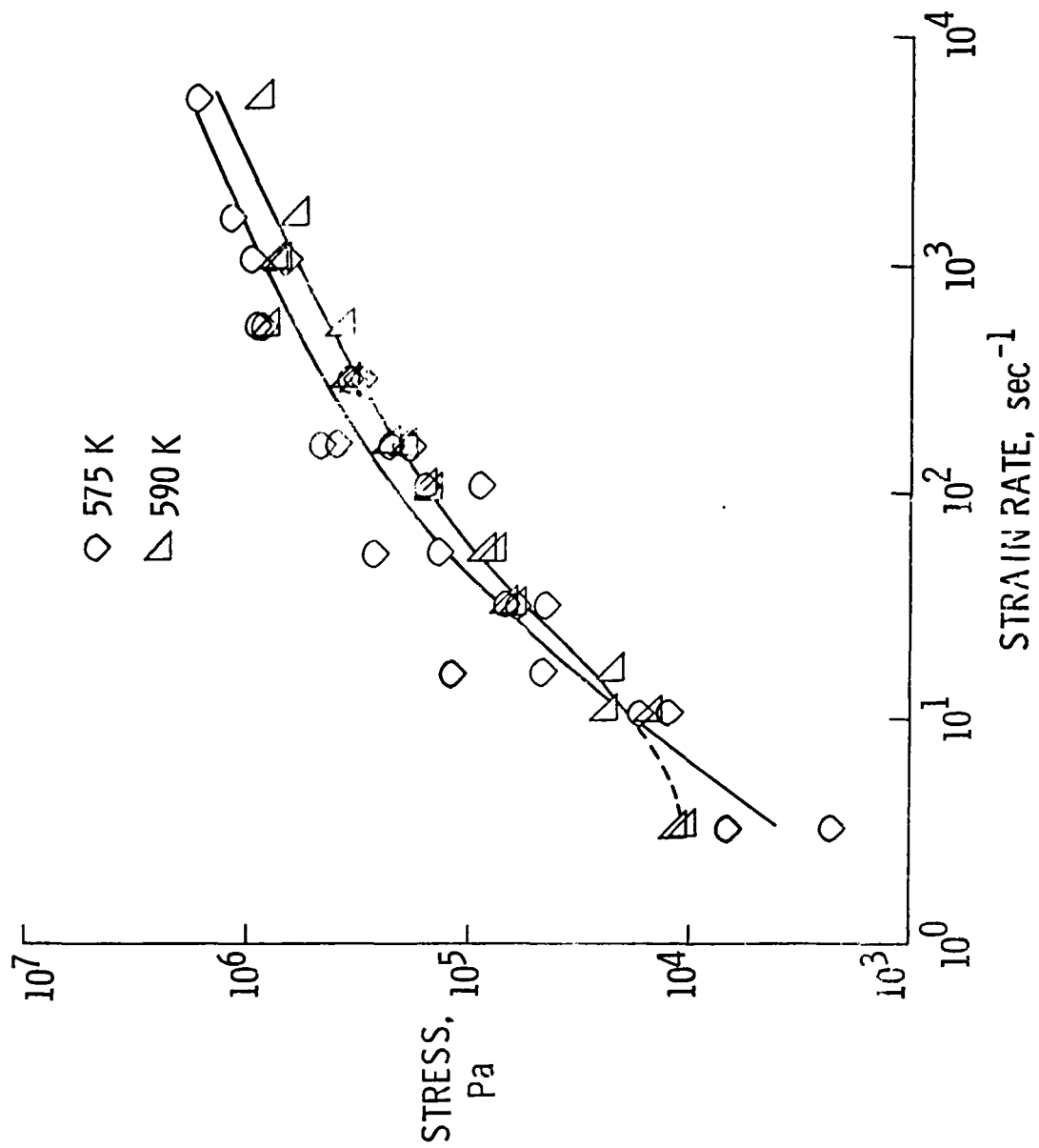
FLOW CURVES OF POLYIMIDE V-200



FLOW CURVES OF POLYIMIDE V-230

The test temperatures for the V-230 were restricted for the same reasons as those described previously for the V-200. However, the V-230 data generally fell between the 575 and 590 K curves of the V-200. The 575 K data had a considerable amount of scatter which seemed to be influenced by the capillaries and drive gears used in the tests. Such scatter made an accurate location and shape of the flow curve very difficult, and thus may be one reason the 575 K curve for the V-230 fell below that for the V-200. By contrast, the 590 K curve for the V-230 generally was above that of the V-200 as would be expected due to the higher T_g . The apparent compressibility effect also was observed with the 590 K data at the lowest strain rates.

FLOW CURVES OF POLYIMIDE V-230

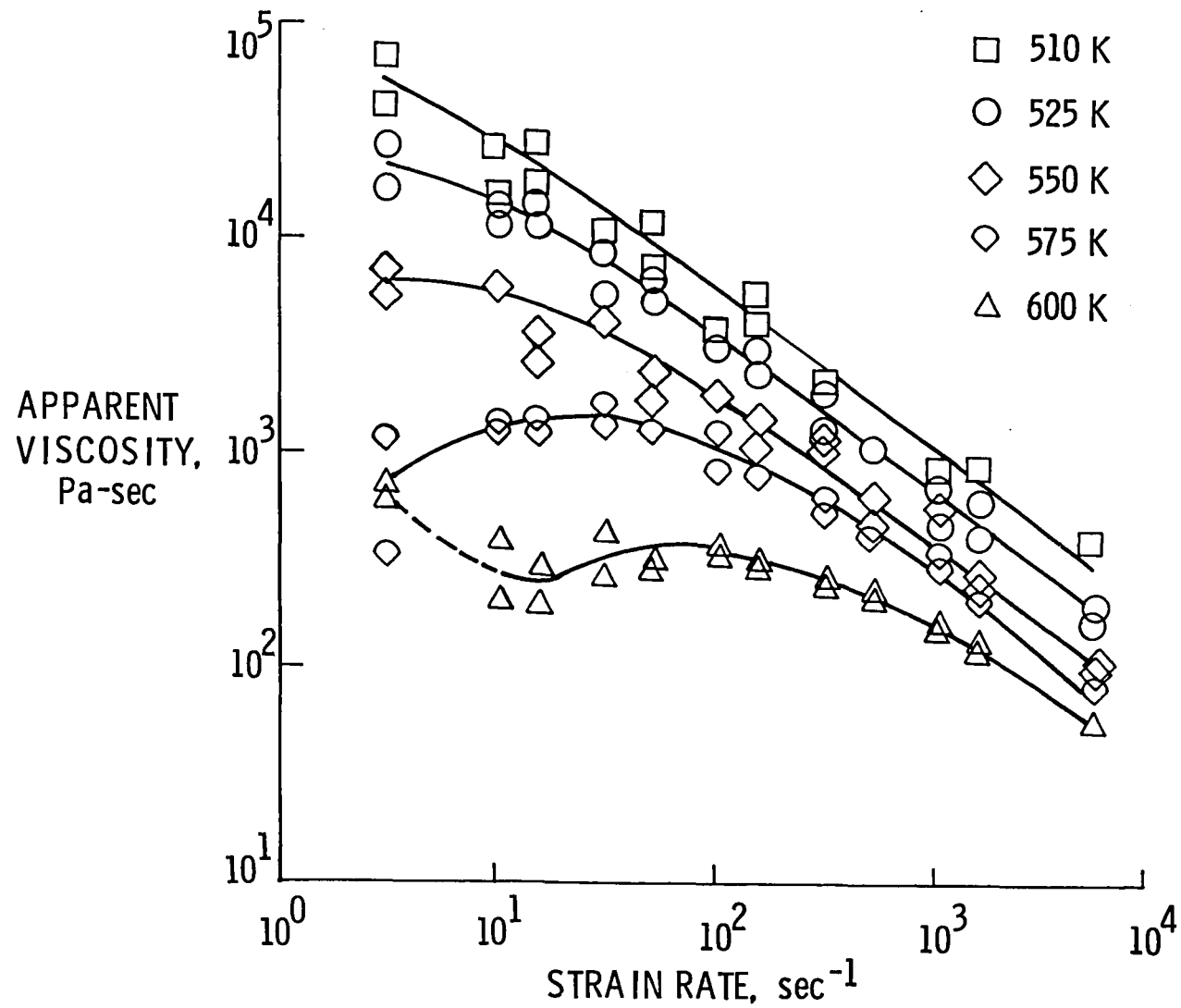


VISCOSITY OF POLYIMIDE V-167

The apparent viscosity of the polymers was calculated by dividing the flow stress by the strain rate. As the strain rate was calculated from the volumetric flow data and was not corrected to obtain the wall rate, the viscosity is an apparent rather than a true viscosity (ref. 8). The apparent viscosity for the V-167 showed a generally pseudo-plastic response with a low strain rate reversal in the 600 K curve due to the previously mentioned compressibility. The curvature in the 575 K curve may have been a manifestation of compressibility which would have become obvious if tests had been made at even lower strain rates.

For comparison purposes, an epoxy resin at room temperature typically will have a viscosity of 15-25 Pa-sec. These data show that thermoset-like flow, in prepregging for example, might be obtained for the V-167 at high temperatures and high strain rates (with the associated high pressures). By contrast, the molding of a composite material generally takes place at very low strain rates and low pressures. Consequently, the apparent viscosity would be high and very long times would be required to obtain adequate flow in the V-167.

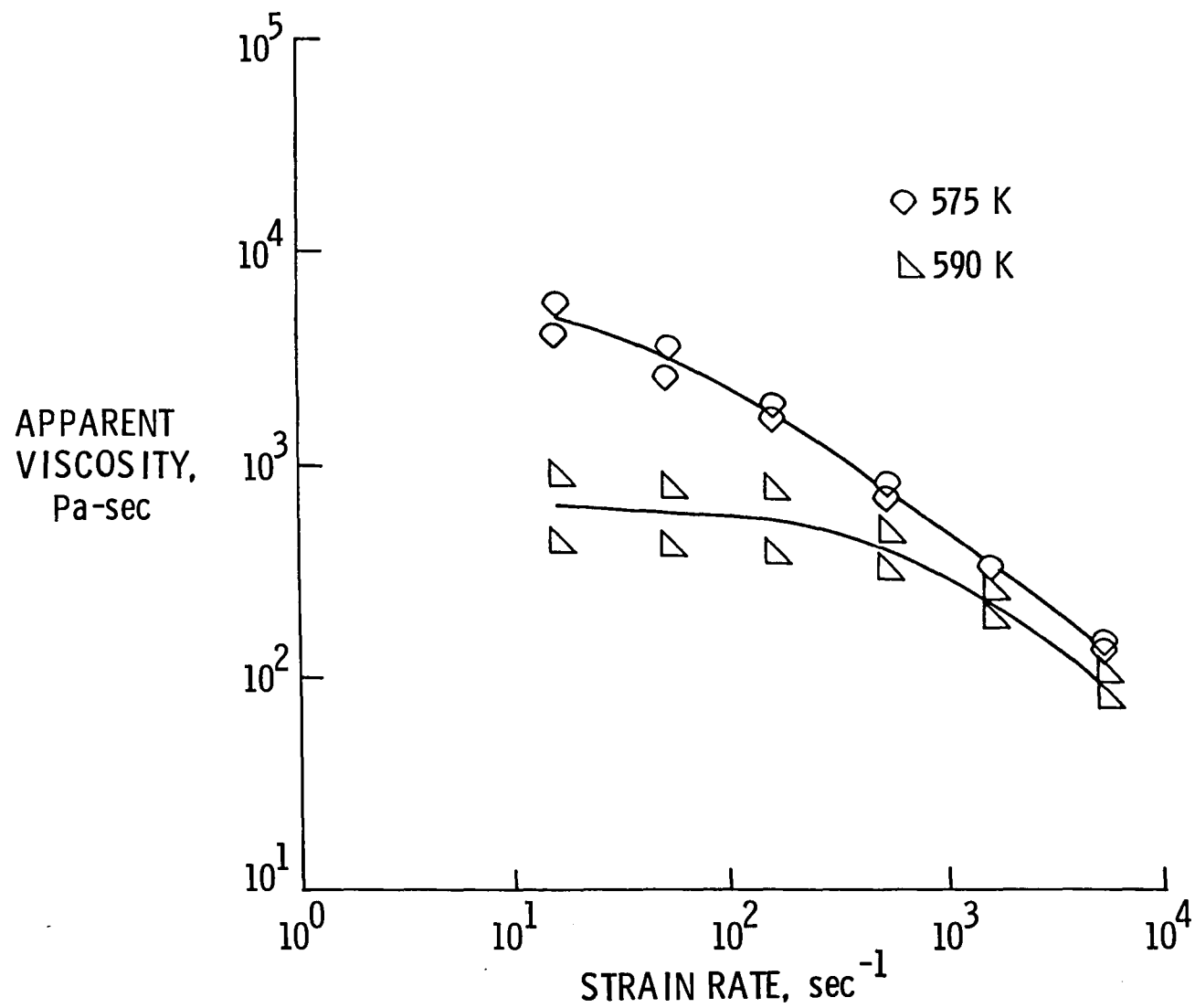
VISCOSITY OF POLYIMIDE V-167



VISCOSITY OF POLYIMIDE V-200

The limited apparent viscosity data for V-200 showed distinct trends, with apparent Newtonian response at the lower strain rates and the two curves (at 575 and 590 K) essentially merging at the higher strain rates.

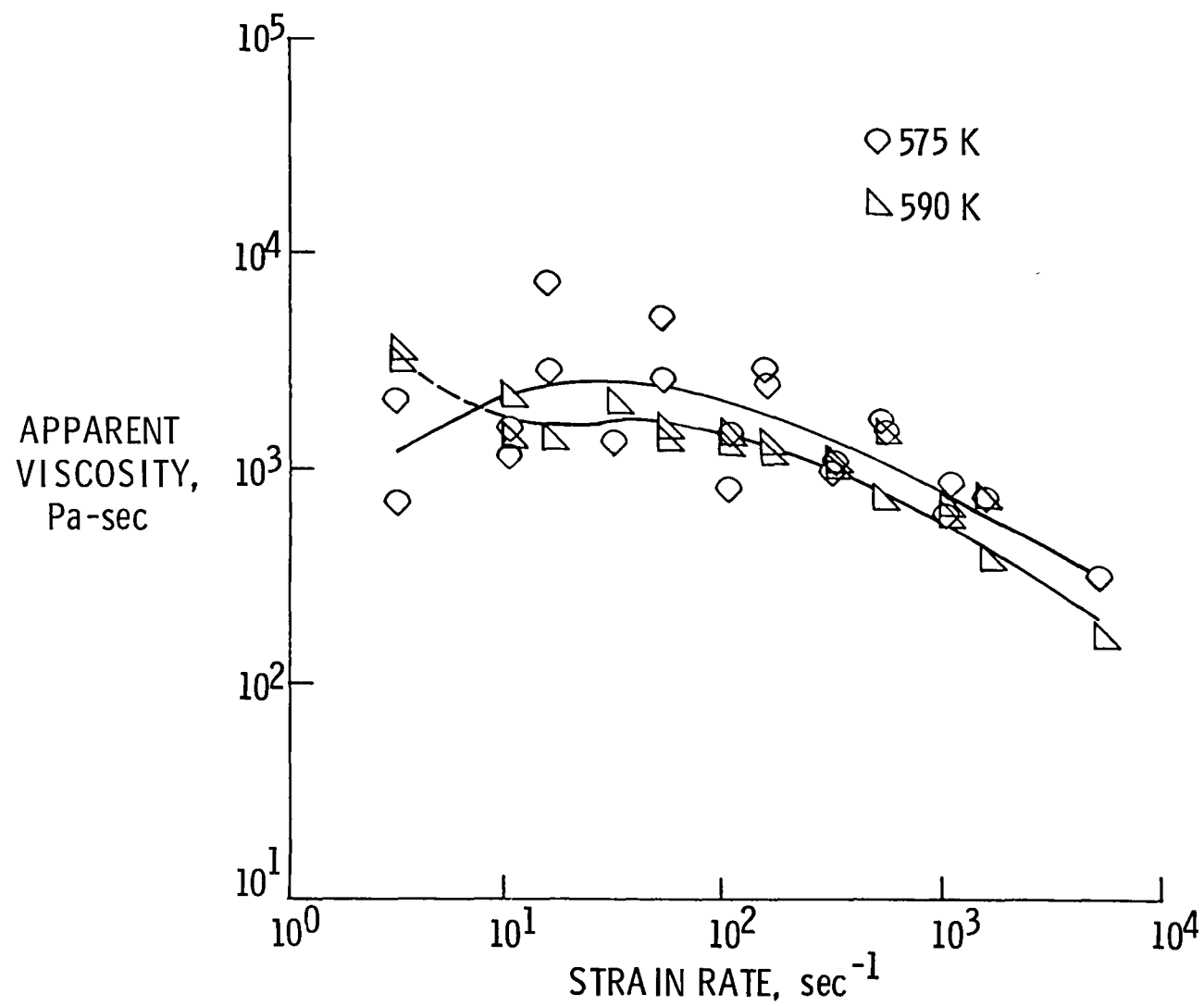
VISCOSITY OF POLYIMIDE V-200



VISCOSITY OF POLYIMIDE V-230

The apparent viscosity curve of V-230 at 590 K reflected the compressibility effects noted in previous discussions. The considerable scatter in the 575 K data apparently was influenced by the capillaries and the drive gears used in the tests.

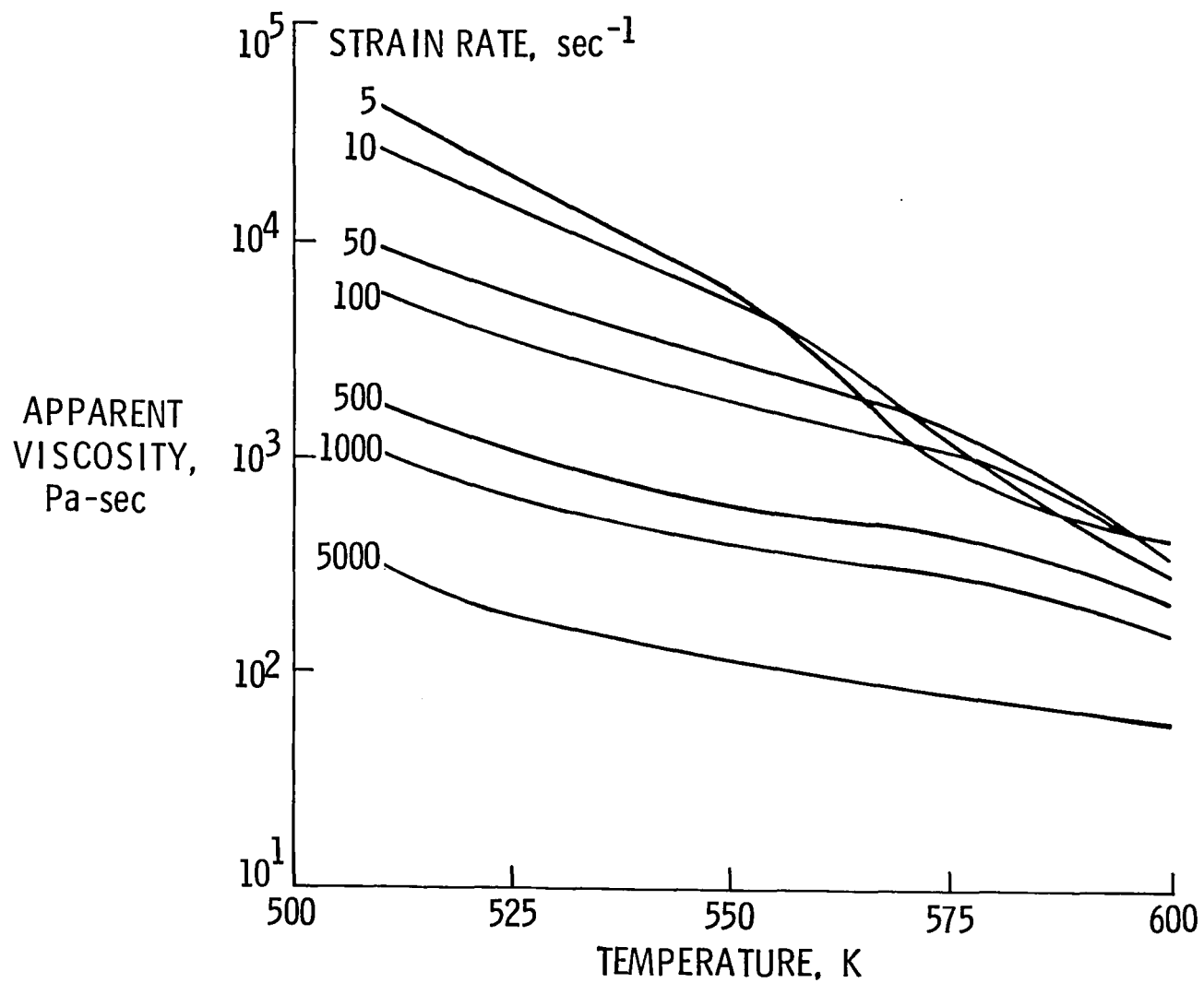
VISCOSITY OF POLYIMIDE V-230



VISCOSITY-TEMPERATURE-STRAIN RATE CURVES FOR POLYIMIDE V-167

Curves of apparent viscosity as a function of temperature for selected strain rates were constructed by cross-plotting the apparent viscosity-strain rate data for the V-167. The curves showed fairly uniform flow behavior without obvious processing "windows." The dip in the 5 and 10 sec^{-1} curves appeared to be related to the compressibility behavior previously described. This dip represented the only possible processing advantage which could be found for the V-167. Curves such as these, together with the flow curves, would be useful in connection with melt prepregging and molding. For example, the prepregging might be considered a coating or calendering operation, in which case the viscosity and extent of Newtonian flow would be important (ref. 9). Such properties would also be of value in the molding process which could be treated as a case of flow (of polymer) through a porous medium (the fibers) as described in reference 10. However, no such analysis was made inasmuch as the data had shown that high pressures, high temperatures, and/or long times were required to obtain adequate flow with these polymers.

VISCOSITY-TEMPERATURE-STRAIN CURVES FOR POLYIMIDE V-167



PROCESSING CONDITIONS FOR POLYIMIDE-CARBON FIBER LAMINATES

Two of the polymers (V-167 and V-230) were fabricated with Celion 6000 carbon fiber into 8-ply unidirectional laminates. No attempt was made to obtain optimum laminates. Rather, the purpose was to test the applicability of some of the information obtained in this investigation. As melt prepregging equipment was not available, a solution prepregging procedure was used. The prepreg was dried at 425 K for 0.5 hour to approximate a melt prepreg condition. Two molding temperatures were selected: 540 K which was a temperature lower than the dip in the viscosity-temperature curve for the V-167; 583 K which was a temperature in the dip region. These temperatures were 22 and 32 percent higher than the V-167 T_g . The 583 K temperature was used for the V-230, a temperature which was 16 percent higher than T_g . Long molding times (for thermoplastics) of 1 and 2 hours were used. Although both a molding press (for the V-167) and an autoclave (for the V-230) were used, the pressure was limited to that (1.4 MPa) which could be obtained in the autoclave.

PROCESSING CONDITIONS FOR THERMOPLASTIC POLYIMIDE-CARBON FIBER LAMINATES*

POLYMER	METHOD	TEMPERATURE, K	TIME, hr
V-167	PRESS (A)	540 (1.22 T _g)	2
	PRESS (B)	583 (1.33 T _g)	1
V-230	AUTOCLAVE	583 (1.16 T _g)	1

* ALL LAMINATES OF CELION 6000 MOLDED UNDER 1.4 MPa PRESSURE
AFTER DRYING AT 425 K FOR 0.5 hr

SHORT BEAM SHEAR STRENGTH OF POLYIMIDE-CARBON FIBER LAMINATES

The short beam shear strength of the laminates had a room temperature average of 57 MPa, very close to the 55 MPa value for a thermosetting polyimide, carbon fiber (PMR 15/HTS), 8-ply unidirectional laminate (ref. 9). However, the coefficient of variation was generally much higher than that (~ 0.05) in reference 9. For the V-167, the higher molding temperature and shorter time did not provide noticeably better laminates. The strength decreased to ~ 85 percent of the 300 K value at 350 K ($\sim 0.79 T_g$), but then dropped considerably to ~ 34 percent at 425 K ($\sim 0.96 T_g$). By contrast, the strength of the V-230 laminates, which appeared to be poorly consolidated, was affected very little by temperature even though the 425 K test temperature was $0.84 T_g$ for that polymer. While no attempt was made to obtain the "best" laminates, the laminates showed that it is possible to use thermoplastic polyimides as carbon fiber composite material matrices if high molding temperatures and long times are employed. However, processing conditions for these experimental thermoplastic polyimide composites investigated in this study were at the extremes of pressures and times which are typically utilized in conventional autoclave consolidation.

SHORT-BEAM SHEAR STRENGTH OF THERMOPLASTIC POLYIMIDE-CARBON FIBER LAMINATES

POLYMER	GLASS TRANSITION TEMPERATURE, K	TEST TEMPERATURE, K		
		300	350	425
V-167 (A)	442	57 (.132)*	50 (.084)	20 (.075)
(B)	442	62 (.073)	51 (.045)	21 (.072)
V-230	504	52 (.225)	60 (.091)	50 (.164)

*STRENGTH MPa AVERAGE OF 8 TESTS WITH COEFFICIENT OF VARIATION SHOWN IN PARENTHESIS

CONCLUDING REMARKS

The flow properties of three experimental thermoplastic polyimides were measured using a capillary rheometer. The softening temperature to degradation temperature range of the polymers was about 440 to 650 K. All of the polymers retained small amounts of solvent as indicated by an increase in T_g as the polymers were dried. The flow properties showed that all three polymers had very high apparent viscosity, and would require high pressures, high temperatures and/or long times to obtain adequate flow in prepregging and molding. The pressures required for laminate fabrication generally were higher than those obtainable in commercial autoclaves and many commercial presses, so commercial processing would have to be done at high temperature and/or long times.

Although not developed for such application, two of the polymers were combined with carbon fibers by solution prepregging. The prepregs were molded into laminates at selected temperatures and times, guided by the results from the flow measurements. These laminates had room temperature short beam shear strengths similar to those of carbon fiber laminates with a thermosetting polyimide matrix. However, the strength exhibited considerable scatter, and given the difficult processing, these polyimides probably would not be suitable for continuous fiber composites.

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TABLE 1.- PLUNGER FORCE FOR EXPERIMENTAL
THERMOPLASTIC POLYIMIDE V-167

Plunger speed,* cm/min	Plunger force, kg, at temperature of . . . K				
	510	525	550	575	600
Capillary 242 - length 1.0080 in., diameter 0.0302 in.					
0.012	212	82	22	1.0	1.9
.04	274	148	61	13	2.1
.06	430	230	41	23	3.0
.12	328	265	129	42	8.2
.2	602	332	94	63	15
.4	392	317	188	84	35
.6	846	469	162	120	44
1.2	693	568	159	159	73
2	1160	524	241	215	107
4	875	688	553	292	153
6	1320	645	356	298	186
20	200	830	493	408	287
Capillary 279 - length 1.9981 in., diameter 0.0301 in.					
0.012	256	104	32	7.5	4.5
.04	334	242	121	29	8.1
.06	560	358	112	39	9.2
.12	630	346	262	109	27
.2	773	535	254	121	33
.4	780	660	393	260	78
.6	1245	724	447	236	98
1.2	1290	774	720	376	160
2	----	1100	636	446	237
4	1670	948	1175	710	339
6	----	1863	840	623	420
20	----	2000	1090	793	623

* Drive gear ratio 1/5 used for 0.012, 0.04, 0.12, 0.4, 1.2, and 4 cm/min.; ratio 1/1 used for 0.06, 0.2, 0.6, 2, 6, and 20 cm/min.

TABLE 2.- PLUNGER FORCE FOR EXPERIMENTAL
THERMOPLASTIC POLYIMIDE V-200

Plunger speed,* cm/min	Plunger force, kg, at temperature of . . . K	
	575	590
Capillary 242*		
0.06	62	6.6
.2	132	20
.6	250	57
2	358	158
6	488	296
20	668	405
Capillary 279*		
0.06	180	27
.2	360	81
.6	569	229
2	816	488
6	1028	775
20	1480	1068

*Drive gear ratios and capillary
dimensions same as in Table 1.

TABLE 3.- PLUNGER FORCE FOR EXPERIMENTAL
THERMOPLASTIC POLYIMIDE V-230

Plunger speed,* cm/min	Plunger force, kg, at temperature of . . . K	
	575	590
Capillary 242*		
0.012	6.5	11
.04	16	22
.06	113	22
.12	61	64
.2	251	71
.4	150	148
.6	445	183
1.2	289	308
2	850	356
4	618	641
6	1115	580
20	1620	840
Capillary 279*		
0.012	4.3	20
.04	23	29
.06	88	41
.12	85	119
.2	260	160
.4	167	278
.6	750	425
1.2	638	666
2	1560	1508
4	1780	1440
6	----	----
20	----	----

*Drive gear ratios and capillary
dimensions same as in Table 1.

1. Report No. NASA TM-83115		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle FLOW PROPERTIES OF A SERIES OF EXPERIMENTAL THERMOPLASTIC POLYIMIDES				5. Report Date April 1981	
				6. Performing Organization Code 505-33-33-02	
7. Author(s) Harold D. Burks, James B. Nelson and Howard L. Price				8. Performing Organization Report No.	
				10. Work Unit No.	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics & Space Administration Washington, DC 20546				14. Sponsoring Agency Code	
15. Supplementary Notes Presented as a talk at the Society of Rheology 52nd Annual Meeting, Williamsburg, Virginia, February 23-25, 1981.					
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17. Key Words (Suggested by Author(s)) Thermoplastic polyimides Capillary Rheometer Flow properties Carbon fiber laminates			18. Distribution Statement Unclassified - Unlimited Subject Category 27		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 27	22. Price* A03		

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NASA Technical Memorandum 83117

NASA-TM-83117 19810016818

EVALUATION OF SEVERAL ULTRASONIC FLOWMETER TRANSDUCERS IN CRYOGENIC ENVIRONMENT

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APRIL 1981

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EVALUATION OF SEVERAL ULTRASONIC FLOWMETER

TRANSDUCERS IN CRYOGENIC ENVIRONMENT

W. Clayton Moughon
Langley Research Center

SUMMARY

In Langley Research Center's National Transonic Facility, the flow of large quantities of liquid nitrogen (450 Kg-sec^{-1}) will be measured using an ultrasonic flowmeter. The sensing mechanism employed uses piezoelectric transducers which cause an interaction of acoustic waves with the moving fluid to measure fluid velocity (ref. 1). This paper summarizes the result of thermal cycle tests (295 K to 77 K) performed on various ultrasonic flowmeter transducers from four manufacturers to determine their suitability and reliability for this critical measurement. The tests were performed at a pathlength of 66 cm which simulates that of the NTF flowmeter. Although one Millis Research transducer failed after 51 thermal cycles, test results disclose that all transducers tested have the potential for meeting NTF requirements. However, the epoxied-lead metaniobate displayed the strongest signals and the least signal loss per thermal cycle.

INTRODUCTION

Ultrasonic flowmeters are completely nonintrusive and therefore offer no impedance to fluid flow, have no moving parts, and cover a wide flow range of 100:1 or greater. They are an ideal device for liquid flow measurements. When first used to measure cryogenic fluids however, they proved to be somewhat unreliable because of the inability of the piezoelectric sensors to withstand, for practical periods, the rigors of repeated extreme temperature cycling (295 K to 77 K). This problem was first experienced by Langley researchers in the development of the Shuttle pogo flowmeter and only after concentrated efforts by American and French engineers was the ultrasonic flowmeter rendered useful in the measurement of lox and LN_2 . Because of its desirable features the ultrasonic flowmeter was selected for measuring and controlling the NTF LN_2 flow. To assure its suitability for this application, laboratory durability tests were conducted using 18 ultrasonic transducers, all candidates for the NTF flowmeter (fig. 1). The purpose of this paper is to report the results of these laboratory tests which included several different type transducers (American and French), under simulated NTF flow conditions in order to determine their long-term reliability. Identification of commercial products in this report is used to adequately describe the model. The identification of these commercial products does not constitute official endorsement, expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

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Test Apparatus

Test apparatus included an open-top rectangular tank constructed of 3-mm-thick aluminum plate 135-cm long, 33-cm deep, and 33-cm wide (fig. 2). A smaller tank was also constructed 120-cm long, 22-cm deep, and 17-cm wide and this was placed inside the larger tank with 8 cm of insulation separating the two tanks (figs. 2 and 3). The small inner tank was the actual test chamber and both tanks were filled with liquid nitrogen. A polyvinylchloride (PVC) adaptor was constructed for holding the transducers. The transmission pathlength was approximately 66 cm. A pulse-echo device (fig. 3) was used to excite the transducer and measure the return signal in order to determine the active life of the crystal and its ability to generate adequate flow sensitive signals without distortion or ringing. All signals were monitored and measured on a dual-beam oscilloscope. Transducer A was tested first and then connections C1 and C2 were switched and transducer B was tested.

PROCEDURE

Eighteen candidate ultrasonic transducers were selected from the following manufacturers: Panametrics, Millis, ONERA, and MAPCO, Inc. Each transducer was installed (in pairs) in an adapter with a transmission pathlength (66 cm) equal to that of the NTF flowmeter. This adapter was then lowered into a styrofoam insulated tank and filled with LN₂. After reaching 77 K, the transducers were then excited with a pulse-echo device and the signal strength measured on a dual beam oscilloscope. After allowing transducers to soak for from 1 to 4 hours, the signal strength was measured again. The adaptor was then removed and allowed to come to ambient temperature. This procedure was repeated a number of times (Table 1) until the testing was completed.

RESULTS

Panametrics Transducers

Two 15-cm-long transducers, 1 MHz epoxied PZT crystal (lead-zirconate-titanate) were thermally cycled. No. 1 was cycled 82 times and No. 2, 58 times. After all tests, both transducers remained active although the signal level was about 20 dB down from 1.5 Vpp. The attenuated signals were nevertheless of sufficient strength to trigger established electronic processing circuits. Two 5-cm-long transducers, 2 MHz epoxied K-81 crystal (lead metaniobate), were also thermally cycled. No. 3 was cycled 77 times and No. 4, 67 times. After all tests, signals were strong at approximately 2 to 2.5 Vpp.

Two other 5-cm-long transducers, 2 MHz soldered PZT crystals (lead metaniobate), were then thermally cycled. No. 5 was cycled 54 times and No. 6, 58 times. After all tests signals were strong at approximately 1 to 2.5 Vpp. (See Table 1.)

All six transducers remained active after all thermal cycle tests.

Millis Research Transducers

The Millis Research Transducers are unique in that the crystal is bonded to a graphite damping material and the stainless steel transducer tip by a thermal diffusion method which was developed by Millis Research Corp. This technique involves tinning both sides of the crystal, the transducer tip, and the damping material with a special solder mixture (proprietary) and producing the bond in a high temperature welding machine.

Initially six 15-cm long, 1 MHz, PZT soldered transducers were thermally cycled. No. 1 and No. 2 were each cycled 60 times and retained strong output signals between 0.9 and 1.2 Vpp. No. 3 was thermally cycled 51 times and retained strong transmission signals between 1.0 and 1.5 Vpp. During testing, No. 4 suffered a separated crystal at the transducer tip. The stainless steel cover (transducer tip) oil canned and separated from the crystal which blocked acoustic transmission although the crystal itself remained active. No. 5 and No. 6 were cycled 59 times and retained a strong signal between 0.7 Vpp and 1.1 Vpp. (See Table 1.)

ONERA Transducers

Four ONERA transducers (Office Nationale D'Etudes et des Recherches Aerospatiales of France), 2 MHz PZT (lead-zirconate-titanate), electron beam welded tips, were all thermally cycled 35 times and none showed any degradation of the signal between 2 Vpp and 3 Vpp. These transducers were a later generation than those used in the Shuttle pogo flowmeters designed by ONERA to investigate pogo-induced flow oscillation in the Shuttle lox feed lines. (See Table 1.)

MAPCO

The MAPCO transducers were thermal cycled 10 times and maintained clean output signals of 1.5 Vpp throughout testing (Table 1).

It is interesting to note that these (same) transducers were originally in a (prototype) ultrasonic flowmeter being tested with LN₂ at the National Bureau of Standards, Boulder, Colorado. During testing (June 1978) the electronics failed and had to be returned to the manufacturer for redesign. This took over 1 year. Meanwhile, the flowmeter body (with transducers) was left in the line at NBS while other testing continued. A meter was connected to the transducers to monitor their activity. During this period the transducers were thermal cycled over 150 times with no loss of signal.

CONCLUSION

Eighteen ultrasonic flow transducers were thermally cycled between 295 kelvin and 77 kelvin repeatedly and their signal strength measured at simulated NTF conditions. The data show that the transducers performed satisfactorily and would be suitable for NTF cryogenic measurements. Since the NTF flowmeter will be occasionally subjected to thermal cycling these tests were performed to determine the endurance and reliability of the transducers when subjected to extreme temperature differences. Because of these favorable test performances it is felt that the problem of transducer reliability in cryogenic ultrasonic flowmeters has been virtually eliminated.

REFERENCE

1. Carpinì, T. D. and Monteith, J. H.: "An Ultrasonic Flowmeter for Measuring Dynamic Liquid Flow, NASA TM 78798, October 1978.

APPENDIX A

TRANSDUCER MANUFACTURERS

Panametrics--Panametrics, Inc., Waltham, MA

Millis--Millis Research Laboratory, Boston, MA

ONERA--Office National D'Etudes et des Recherches Aerospatiales,
Chalillon, France

MAPCO--Mid-American Pipeline Company, Tulsa, OK

TRANSDUCER IDENTIFICATION									TEST RESULTS		
MANUFACTURER	S/N	MATERIAL					SIZE		OUTPUT IN VOLTS (pp)		
		BONDING TECHNIQUE	CRYSTAL	DAMPING	HOUSING	TRANSMIT FREQUENCY	LENGTH	DIAMETER	NUMBER THERMAL CYCLES	FIRST TEST	FINAL TEST
Millis	1	Thermal Diffusion	*LZT	Graphite	Stainless Steel	1 MHZ	15 cm	20 mm	60	1.2	1.0
Millis	2	Thermal Diffusion	LZT	Graphite	St. Steel	1 MHZ	15 cm	20 mm	60	1.0	.90
Millis	3	Thermal Diffusion	LZT	Graphite	St. Steel	1 MHZ	15 cm	20 mm	51	1.5	1.0
Millis	4	Thermal Diffusion	LZT	Graphite	St. Steel	1 MHZ	15 cm	20 mm	51	Separated Crystal	NA
Millis	5	Thermal Diffusion	LZT	Graphite	St. Steel	1 MHZ	15 cm	20 mm	59		0.6
Millis	6	Thermal Diffusion	LZT	Graphite	St. Steel	1 MHZ	15 cm	20 mm	59		0.7
Panametrics	1	Epoxied	LZT	Graphite	St. Steel	1 MHZ	15 cm	20 mm	82		1.35
Panametrics	2	Epoxied	LZT	Graphite	St. Steel	1 MHZ	15 cm	20 mm	58	1.5	1.35
Panametrics	3	Epoxied	**LM	Graphite	St. Steel	2 MHZ	5 cm	20 mm	77	2.6	2.5
Panametrics	4	Epoxied	LM	Graphite	St. Steel	2 MHZ	5 cm	20 mm	67	2.1	2.0
Panametrics	5	Soldered	LM	Graphite	St. Steel	2 MHZ	5 cm	20 mm	54	1.2	1.0
Panametrics	6	Soldered	LM	Graphite	St. Steel	2 MHZ	5 cm	20 mm	58	2.5	2.5
ONERA	1	Adhesive									
		Methacrylate	LZT	Lucite	St. Steel	2 MHZ	7 cm	10 mm	35	2.0	2.0
ONERA	2	Adhes. Meth.	LZT	Lucite	St. Steel	2 MHZ	7 cm	10 mm	35	2.7	2.7
ONERA	3	Adhes. Meth.	LZT	Lucite	St. Steel	2 MHZ	7 cm	10 mm	35	2.6	2.6
ONERA	4	Ester Anerobic Glue	LZT	Lucite	St. Steel	2 MHZ	7 cm	10 mm	35	2.2	2.1
MAPCO	1	Oil Seal	Unknown	Oil Seal	Teflon	1.5 MHZ	12 cm	27 mm	10	1.5	1.5
MAPCO	2	Oil Seal	Unknown	Oil Seal	Teflon	1.5 MHZ	12 cm	27 mm	10	1.6	1.5

* Lead Zirconate Titanate

** Lead Metaniobate

Table 1. Specification and Test Results for 18 Ultrasonic Transducers Tested for the National Transonic Facility Flowmeter.

NASA
7-570

ONERA Transducer

Panametrics Transducers



Figure 1. Types of Ultrasonic Flow Transducers Evaluated in This Paper.

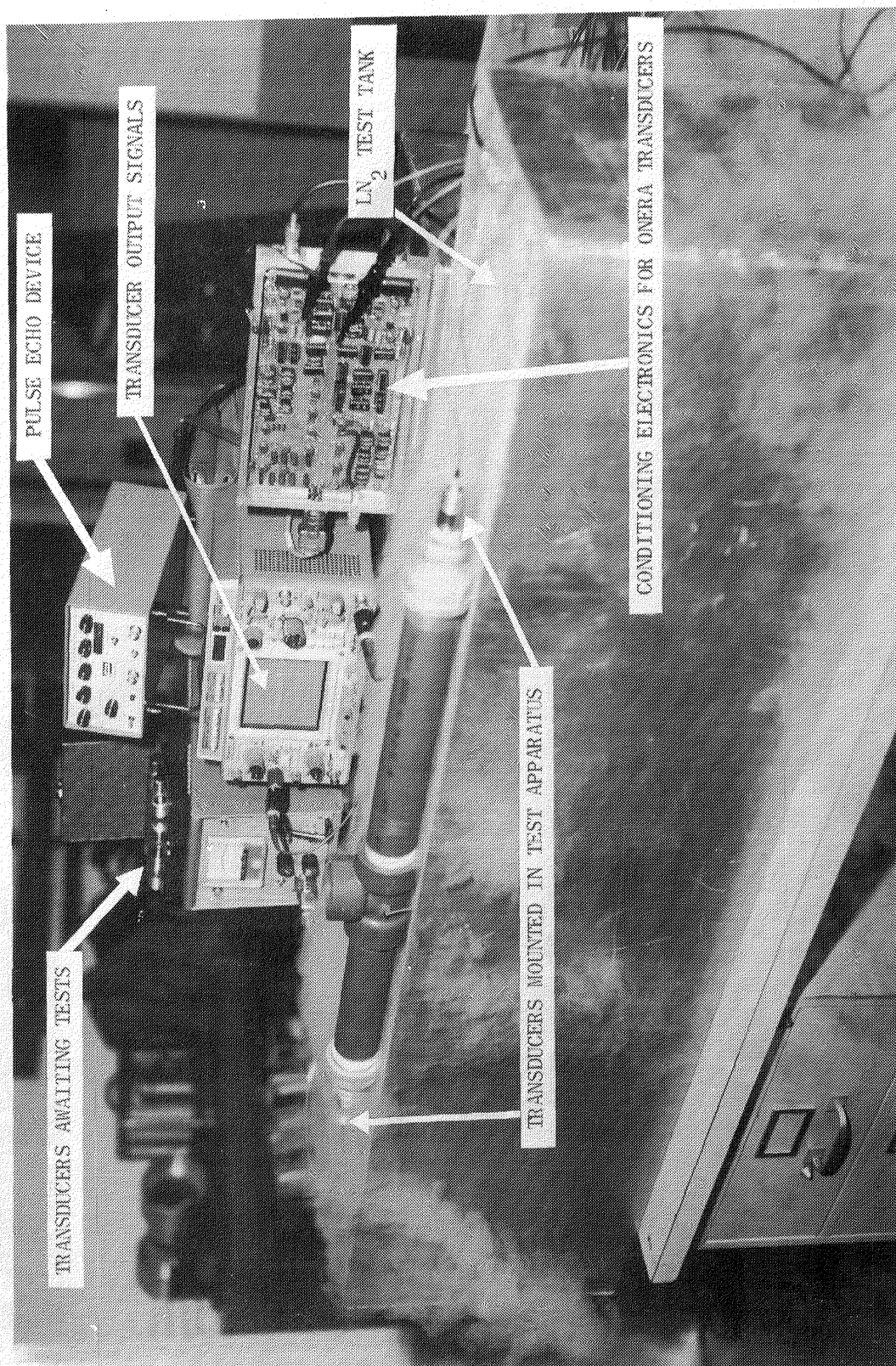


Figure 2. Test Apparatus for the Evaluation of Several Ultrasonic Flowmeter Transducers.

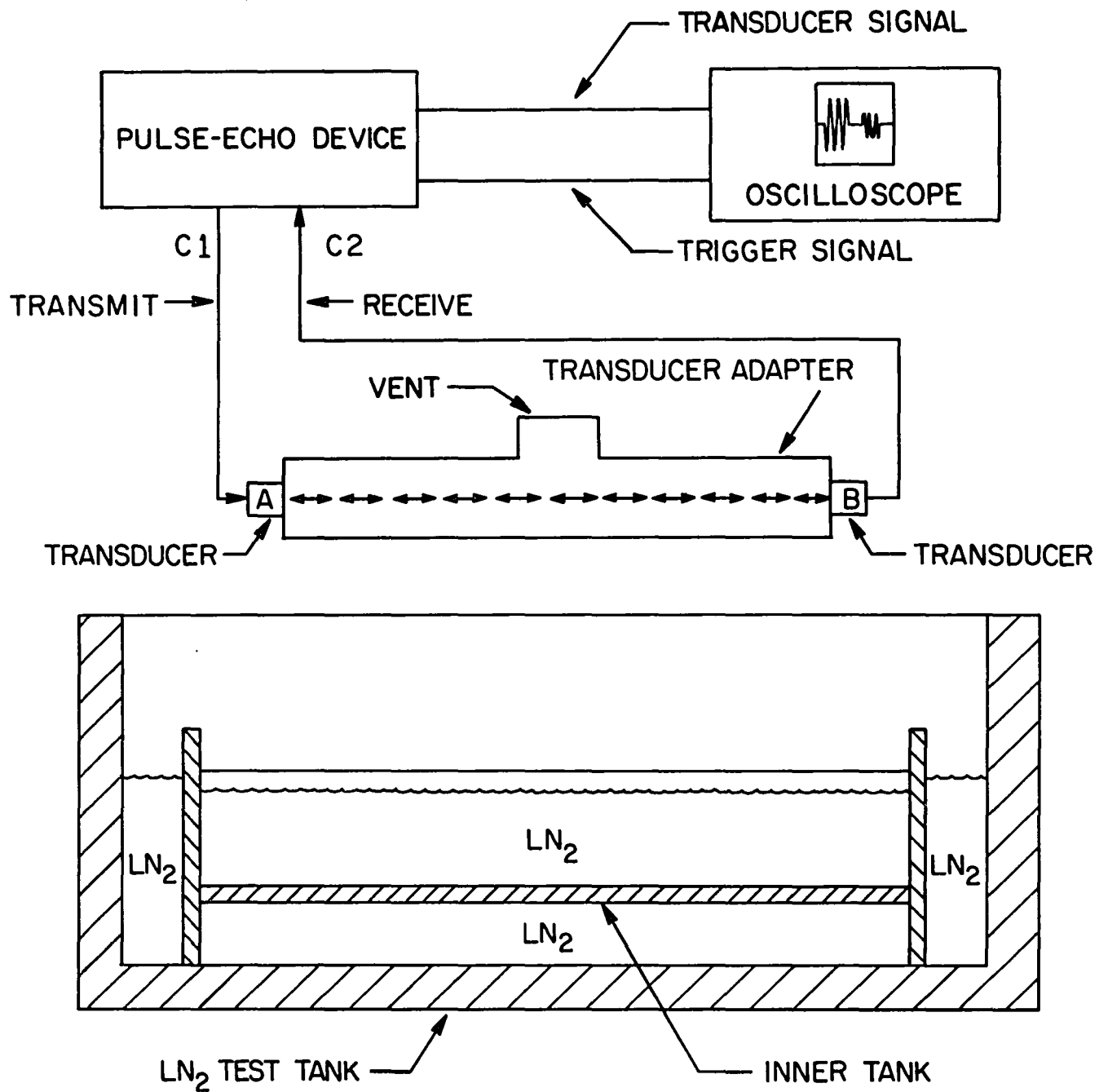


FIGURE 3 - BLOCK DIAGRAM OF THE ULTRASONIC FLOW TRANSDUCER TEST APPARATUS.

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